行政院國家科學委員會專題研究計畫 成果報告

氮化鎵介觀尺度下量子局限結構之光子幅射可控性研究 (3/3)

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行政院國家科學委員會補助專題研究計畫 ■ 成 果 報 告
□期中進度報告

Research on Mesoscopic GaN Quantum Confined Structures for Control of Photon Emission

氮化鎵介觀尺度下量子局限結構之光子幅射可控性研究

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Research on Mesoscopic GaN Quantum Confined Structures for Control of Photon Emission

氮化鎵介觀尺度下量子局限結構之光子幅射可控性研究

總執行期限：2003/08/01 ~2006/07/31

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Abstract

We have accomplished the objectives of this three year project. The main accomplishments include successfully fabrication of high-density InGaN quantum dot (QD), fabrication, optical and device properties of GaN-based nanorods, growth and study of high-reflectivity crack-free GaN/AlN DBR, fabrication and characteristics of optically pumped GaN-based VCSEL with two different micro-cavity structure, GaN quantum whispering gallery light emitting laser and sub-micro triangular rods formed by using photo-enhanced wet oxidation and crystallographic etching technique, .

摘要

本研究團隊已經完成本三年期計畫所規劃之研究目標。包括建立光學微共振腔之低維氮化鎵量子點、柱結構生長與製作，以及高品質無裂縫之氮化鎵、氮化鋁布拉格反射鏡與量子點之磊晶成長研究，奈米柱之光學微共振腔物理性質量測與分析與奈米柱元件製作、兩種不同的光激發之氮化鎵面射型雷射之微共振腔結構製作與特性分析，並以自組式光致氧化與蝕刻技術，製作微共振腔以達雷射操作與次微米三角奈米柱並研究其特性。

報告內容

(一) 前言

本文為奈米國家型科技計畫之氮化鎵介觀尺度下量子局限結構之光子輻射可控性研究之完整成果報告，內容為針對本計畫在三年的計畫執行期間進行研究之實驗方法、成果以及所發表之文獻。

(二) 研究目的

本研究計畫主要的研究目的是觀察介觀尺寸下氮化鎵基具量子侷限的結構，並藉此得到一光子可控制的量子侷限結構，觀察該結構之光學特性。本計畫將針對以下幾點作深入的研究，包括：(1) 研究發展並製作高量子侷限效果的氮化鎵量子侷限結構，像是量子點、量子柱等；(2) 模擬並建立一套模型以分析量子侷限微共振腔之光學特性，藉此作為元件設計製作之設計方向；(3) 製作一高品質氮化鎵微共振腔之面射型雷射結構；(4) 觀察以上製作出來的面射型雷射之光學與元件特性；(5) 利用製作完成支微共振腔面射型雷射，觀察並展現其從量子侷限微共振腔控制光子輻射之現象。

在研究方法上，將依照三年的計畫完成以上之研究目的，第一年主要研究發展量子

侷限元件的主要製作技術，如高品質磊晶層之磊晶成長、光電化學蝕刻和乾蝕刻設備的建立和實現；第二年則建立模擬成果和元件包括奈米柱和面射型雷射元件的實現；第三年則是利用完成之元件實現可控制光子輻射。

(三) 文獻探討

史丹佛大學 Y. Yamamoto 教授利用光學微共振腔結構成功控制單光子控制輻射元件，其研究領域囊括光學微共振腔結構之磊晶動力學機制，成長量子點、量子柱低維結構。應用雷射光譜、表面分析、電性量測等技術，配合能隙理論、量子電動力學模型計算，研究壓電效應、庫倫封鎖，對於介觀尺度之氮化鎵低維量子結構之次能帶躍遷、電子之空間穿遂與光電交互作用，探討介觀尺度下之拘限效應對於光子輻射之可控性研究。

腔內量子電動力學的研究題材，也包含了經典原子和腔體輻射的交互作用與量子光學，而在 1980 年代中期達到鼎盛。如 MIT 的 Prof. Kleppner[1]和法國高等師範(Ecole Normale Supéieure) 的 Prof. Raimond 和 Harochei [2]發表過 Rydberg atom 之腔體耦合效應對自發性輻射之抑止和方向性增益的報導。

1997 年，D. L. Huffaker 等人利用分子束磊晶(MBE)之磊晶法，成功地成長出量子點結構之紅外光面射型雷射($In_{0.5}Ga_{0.35}Al_{0.15}As$) [3]。而在氮化物方面，N. Grandjean 利用 MBE 之自行聚集量子點成長法(稱為 Stranski-Krastanov growth) [4]來成長 InGaN/GaN 量子點結構，發現量子點結構有助於增強室溫之 PL 強度。另外，在 1999 年 7 月，德國 Wurzburg 大學 K. Tachibana 之研究群[5]，以及日本東京大學發表了光激發量子點結構的雷射(photo pumping laser)，其臨界光激發強度(threshold pump energy)為 6 mJ/cm2，TE 模式之頻譜，半高寬為 0.1 nm；他們利用 MOVPE 成長 $Al_{0.07}Ga_{0.93}N$ 包覆層(cladding lsyer)和 GaN 波導層(waveguide layer)，而波導層裡有 10 週期之 $In_{0.2}Ga_{0.8}N$ 之量子點，量子大小與高度分別為 19.5 nm 與 4.5 nm，而其每層分布密度為 $6x10^9$ cm^{-2}。H. X. Jiang 研究群將氮化銦鎵量子井結構做成微碟形結構(microdisk)，並觀察出其 Radial 模態，更做成陣列發光二極體。

(四) 研究方法、結果與討論

I. Successfully established growth condition of InGaN quantum dot (QD).

We have successfully grown self-assembled InGaN QDs structure without using any anti-surfactant by metal-organic chemical vapor deposition system (MOCVD). The flat GaN/sapphire structure with an average deviation R_a=0.28nm over an area of 1 μm square was used as the template for InGaN QDs structure (Fig.1(a)). The growth conditions of InGaN QDs were low V/III ratio (~8000) and low growth temperature (660^{o}C). Fig. 1(b) shows the typical surface image of InGaN QDs structure. The QDs density was about 4.5 * 10^{10} cm^{-2} with an average lateral size of 20nm and an average height of 2nm. The interruption growth was used to improve the quality of InGaN QDs and the effect of interruption time (t_{int}) has also been investigated. Our results suggest that the interruption growth can modify the size of InGaN QDs and the emission peak energy. Fig. 2(a) shows the averaged height and diameter of the samples with various interruption times. The mean size (diameter, height) of sample A (t_{int}=30s), B (t_{int}=60s), and C (t_{int}=120s) are (14nm, 2.4nm), (11.5nm, 1.6nm), and (15nm, 2.5nm), respectively.

Fig.2(b) shows the dependence of the coverage above the wetting layer, and QDs density on the interruption time. The coverage increases from 5.2% to 7.2% by increasing t_{int} from 30s to 120s and the QDs density has a maximum value, 4.5 * 10^{10} cm^{-2} at t_{int}=60s. These results implied that ad-atom surface diffusion effect always exists during the process of interruption growth. The coverage increases from 5.2% to 7.2% was an evidence of the mass transfer from wetting layer; the increase in dot density during the growth interruption 30s<t_{int}<60s was cause by mass transfer from wetting layer. The decrease in dot density during growth interruption 60s<t_{int}<120s can be mainly ascribed to the ad-atom surface diffusion, which leads to the enlargement of the largest islands at the cost of the smallest ones due to Ostwald ripening. Fig. 3(a) shows the room temperature PL of these InGaN QDs samples measured using a He-Cd laser as the excitation source. The PL emission peak energy of the InGaN QDs samples is blue-shifted from 2.497eV to 2.735eV as the interruption time increases. We used FEMLAB to calculate the In composition of InGaN QDs. Fig. 3(b) shows the simulation results. It indicated that In composition decreased from 48% to 36% as t_{int} increase from 30s to 120s. It is an evidence of indium desorption which lead to the decrease of the In composition of the InGaN QDs. In Fig. 4, we plot for all samples the spectrally integrated PL intensity as an Arrhenius plot. From the fitting curve with I ∝exp(EA/kBT), we obtained the activation energy E_A for the various sample. For sample A, E_A=63.1meV; for sample B, E_A=89.7meV, and for sample C, E_A=35.0meV. From the above results, It indicated that t_{int}=60s is an optima condition for sample B owning smallest QDs size, largest QDs density and the best optical quality.

Using this technique, indeed, it was feasible for formation of multi layer InGaN QDs structures and applicable for the fabrication of GaN-based light emitting devices.

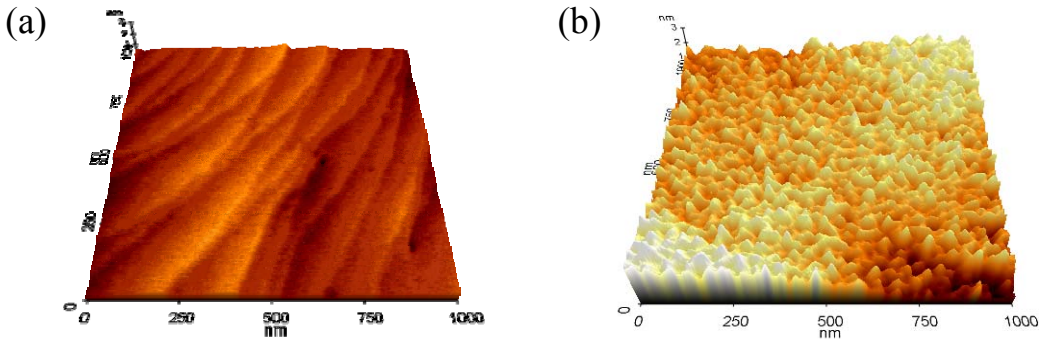


Fig. 1 The surface morphologies of (a) GaN/sapphire template and (b) typical InGaN QDs structure.

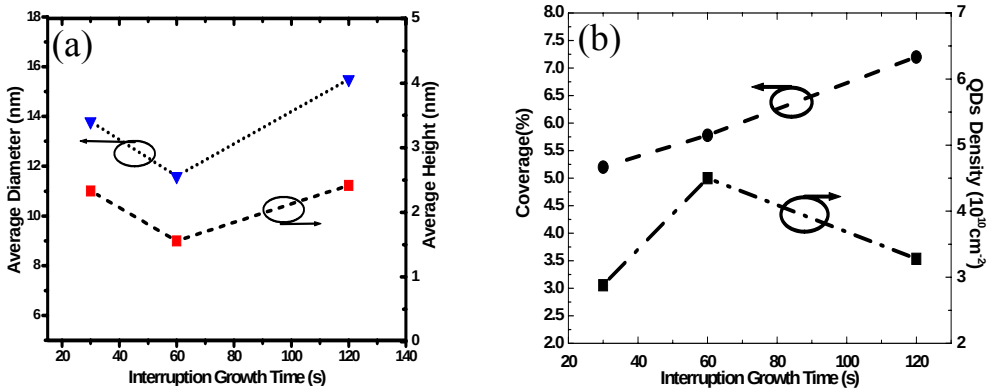


Fig. 2 (a) Average diameter and average height, and (b) InGaN QDs density and the coverage in dependence of the interruption time.

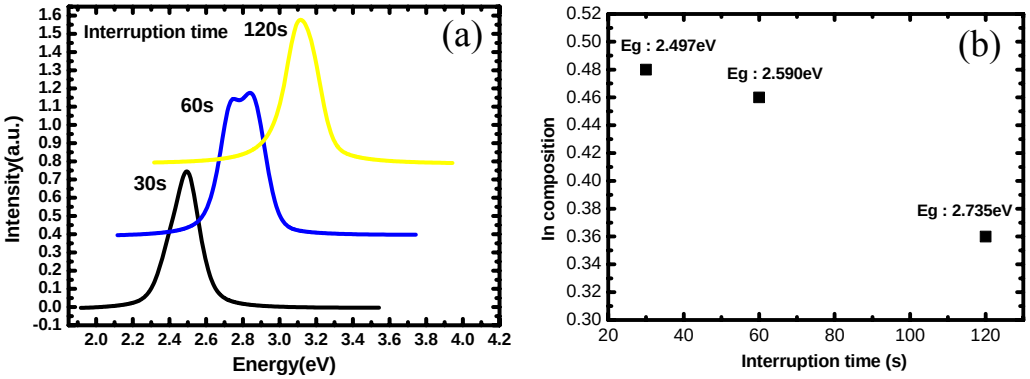


Fig.3 (a) Photoluminescence spectra of these samples at room temperature under an excitation power of 20mW. (b) Simulation results of In composition of InGaN QDs under various interruption time.

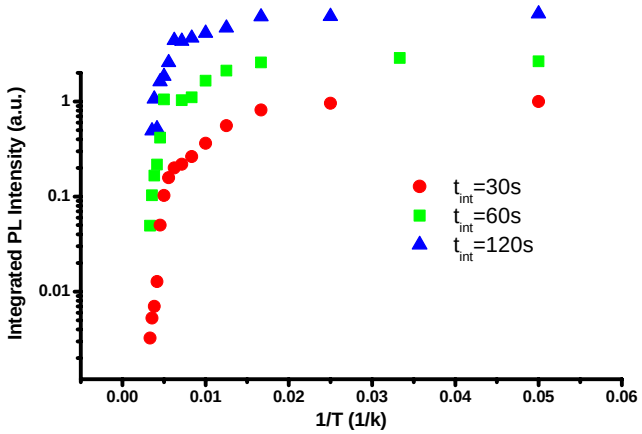


Fig. 4 Arrhenius plots of the integrated PL intensity as a function of temperature.

II. Fabrication and measurement of InGaN/GaN multiple quantum wells nanorods

1. Fabrication of GaN-based nanorods by self-assembled Ni nano-masks and ICP-RIE dry etching

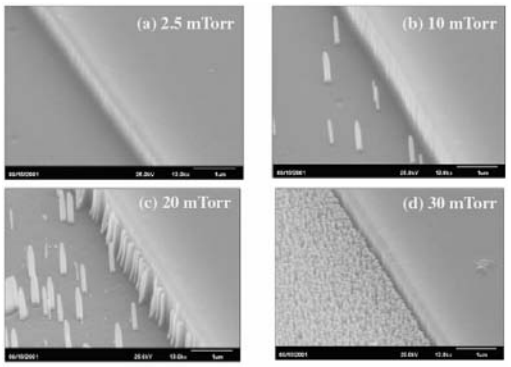


Fig. 5 SEM images of the etched GaN sample surface morphology for different chamber pressures: (a) 2.5 mTorr, (b) 10 mTorr, (c) 20 mTorr and (d) 30 mTorr at the same Cl2/Ar flow rate of 10/25 sccm, ICP/bias power of 200/200W for 2 min etching time.

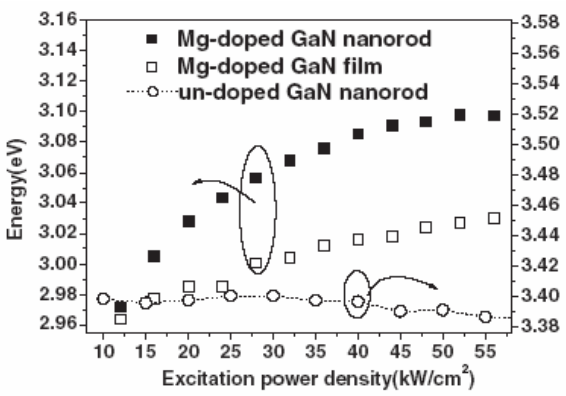


Fig. 6 PL peak energy as function of excitation power density. Filled (open) squares represent Mg-doped GaN nanorod (film) while open circles indicate the undoped GaN nanorod.

In this section, we attempted to study the fabrication and μ-PL characterization of Mg-doped GaN nanorods fabricated from a GaN epitaxial film by self-assembled Ni nano-masks and inductively coupled plasma reactive ion etching (ICP-RIE). A large spectral blueshift of the PL peak was observed for the Mg-doped GaN nanorod with respect to the Mg-doped GaN film. As

shown in the SEM image in Fig. 5(a), a uniform etched surface with no nanorod formation was observed at and below the chamber pressure of 2.5 mTorr, and the surface roughness was approximately 1.5 nm. As the chamber pressure was increased to 10 mTorr, GaN nanorods began to form and the density of the nanorods increased as the chamber pressure was further increased to 20 mTorr and 30 mTorr. The nanorods had a near hexagonal structure with a height of approximately 1 mm as estimated from the SEM images shown in Figs. 5 (b) and (c), and about 0.4 mm at 30 mTorr from Fig. 5(d). The variation in the height of the nanorods seems to be related to the etching rate. In our experiment, the etching rate was approximately 3000 _A/min at 2.5 mTorr, and increased to approximately 5000 _A/min at 10 mTorr and 20 mTorr, and then decreased to 1450 _A/min at 30 mTorr. This seems to correspond to the variation in height of the nanorods. At 30 mTorr, as shown in Fig. 5(d), the nanorods formed a two-dimensional array of uniform density. Figure 6 shows high-resolution SEM images of the high-density Mg-doped GaN nanorods. Figure 5(a) shows the top view image of the Mg-doped GaN nanorods, and the density of the nanorods was estimated to be approximately 3 _ 1010 cm_2. Figure 5(b) shows a high-resolution SEM image of the nanorods exhibiting a nanorod diameter of approximately 50 nm. Figure 6 plots the PL emission peak energy as a function of excitation power density for a Mg-doped nanorod, a Mg-doped GaN film and an undoped GaN nanorod. The PL peak energy increases were 125 meV and 67 meV for the Mg-doped nanorod and Mg-doped GaN film respectively as the excitation intensity varied from 12 kW/cm2 to 56 kW/cm2. The corresponding spectral shift between the nanorod and the non-nanorod peaks ranging from 8 meV to 67 meV within the excitation intensity range indicates stronger the power dependence of the Mg-doped GaN nanorod emission. In contrast, the PL emission peak of the undoped GaN nanorod appeared the same in the same excitation range.

2. Optical properties of blue light MQW nanorods

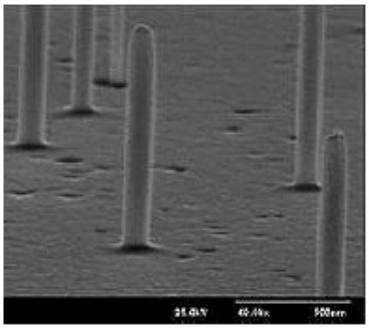


Fig. 7 Scanning electron microscopy image of $In_{0.3}Ga_{0.7}N$/GaN MQWs nanorods.

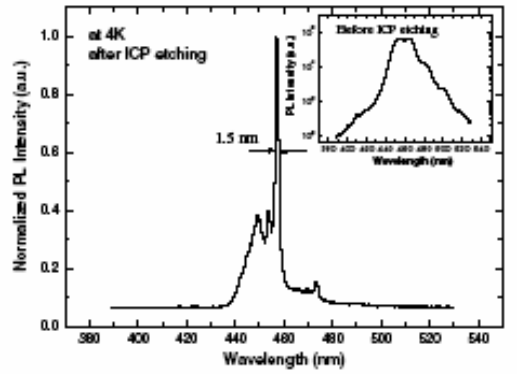


Fig. 8 PL spectrum of $In_{0.3}Ga_{0.7}N$ /GaN MQWs nanorods. The insert is a PL spectrum of the as-grown bulk sample.

Figure 7 displays a typical SEM image of $In_{0.3}Ga_{0.7}N$/GaN MQWs nanorods. The nanorods fabricated by ICP dry etching were almost vertical and straight shape. The nanorods have lengths up to 500 nm and diameters ranging from 60 to 100 nm. Nanorods with diameters less than 55 nm were also observed. About 9~16 nanorods were probed in the μ-PL measurement based on the rod-density of ~ 3×10^8 estimated from fig. 7. A typical PL spectrum of the InGaN/GaN nanorods under an excitation density of 0.9 W/cm^2 was measured at 4 K as shown in fig. 8. It consists of several discrete emission peaks whose positions are at 449, 453 and 457 nm respectively. The

strong narrow emission peak at 457 nm has a full width at half maximum (FWHM) of about 1.5 nm. The position difference between each peak is estimated to be 4 nm (24 meV). The insert in fig. 8 is the spectrum from the as-grown bulk wafer before the ICP etching, which was measured at the same condition for the nanorods. It shows a typical InGaN/GaN MQWs spectrum with a FWHM of about 26.5 nm and an undulation behavior which is probably due to the Fabry-Perot interferences within the epitaxial layers. Indeed, the fabrication of nanorods structure from the $In_{0.3}Ga_{0.7}N$/GaN MQWs bulk wafer does exactly show the different behavior than the typical PL emission spectra of bulk MQWs. This could be due to the decrease of in-homogeneous broadening in wells of nanorods. Figure 9 shows a series of spectra record at different excitation densities between 0.9 and 10.1 W/cm^2 for the $In_{0.3}Ga_{0.7}N$/GaN MQWs nanorods at 4K. Under low excitation densities, the e1-h1 peak at 457 nm is dominant. However, with increasing excitation density, the intensity of peak on the high-energy side of the e1-h1 peak increases. Finally, this peak at 453 nm becomes dominant over the e1-h1 emission.

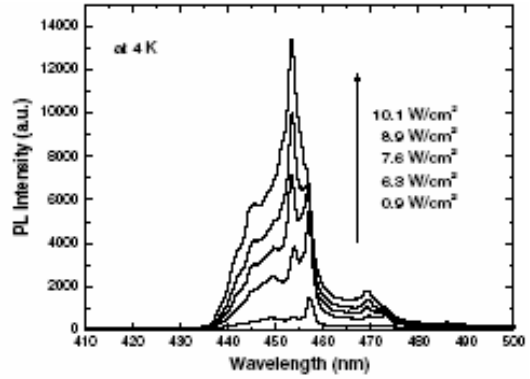


Fig. 9 Excitation power dependent photoluminescence spectra of $In_{0.3}Ga_{0.7}N$/GaN MQWs nanorods.

3. Optical properties of green MQW nanorods

By following the above method, by choosing the appropriate initial Ni thickness, annealing temperature, and annealing time, we can fabricate a self-assembled nanosize Ni masks. In this section, we studied the optical properties of InGaN/GaN MQW green nanorod structures. The optical properties have not been fully studied yet since the higher In content in the *c*-plane MQW could result in lower emission efficiency due to the strong quantum confined Stark effect. In this part, we present the results of enhanced emission intensity properties of InGaN/GaN MQW green emission nanorods and analyze the dominant enhancement mechanism using temperature-dependent PL and time-resolved photoluminescence (TRPL).

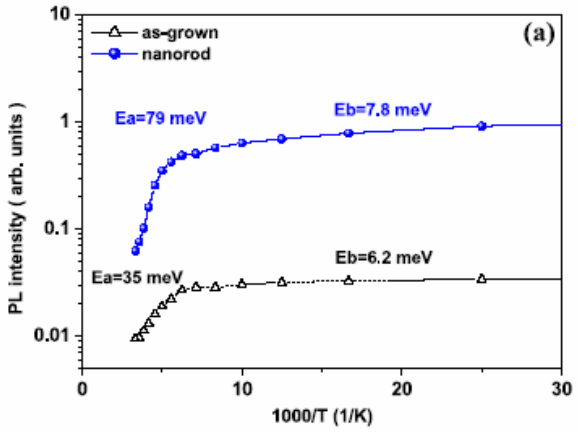


Fig. 10(a) An Arrhenius plot of the integrated PL intensity obtained from the $In_{0.3}Ga_{0.7}N$/GaN MQW active layer emission over the temperature range from 20 to 300 K.

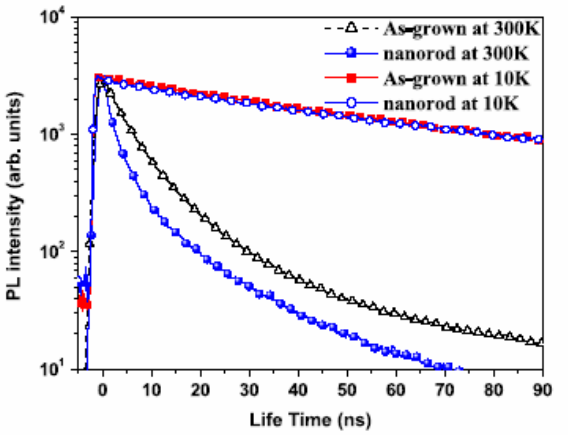


Fig. 10(b) TRPL lifetime curves of the $In_{0.3}Ga_{0.7}N$/GaN MQW as-grown and green emission nanorod samples for the main InGaN emission peak measured at 10 and 300 K.

Figure 10(a) shows an Arrhenius plot of the integrated PL intensity obtained from the $In_{0.3}Ga_{0.7}N$/GaN MQW active layer emission of the as-grown sample and the nanorod sample over the temperature range from 20 to 300 K. The results indicate that the PL intensity of the nanorods is stronger than that of the as-grown sample by a factor of approximately 3.5 at room temperature. Such large emission enhancement could result from improvement either in internal quantum efficiency or external extraction efficiency. The temperature-dependent data of figure 10(a) were fitted with the following formula:

$$IT = I0/[1+A \exp(-Ea/kT)+B \exp(-Eb/kT)]$$

where I_T , I_0 are the integrated PL intensity for T and 0 K, A and B are constants, k is the Boltzmann constant, T is the temperature, Ea is the activation energy for PL quenching, and Eb is generally associated to the free exciton binding energy. The energy Eb of the as-grown and nanorod samples was approximately 6.2 and 7.8 meV, respectively, which was similar to values in the previous report. However, the activation energy Ea of as-grown and nanorod samples was 35 and 79 meV, respectively. Though the high surface ratio around the periphery of the nanorods could provide many non-radiative recombination paths, the larger activation energy of the nanorods obtained seems to suggest that there are higher potential barriers in the nanorods for carriers, where they could easily localize in the effective potential minima of the nanorod structures.

Figure 10(b) shows the carrier lifetime from the as-grown and nanorod samples measured by TRPL at 10 and 300 K respectively. Since a purely radiative recombination at T = 10 K can be assumed, the radiative lifetime of the nanorod sample is similar to that of the as-grown sample, which is approximately 54 ns, indicating that the radiative recombination process for both samples is similar and the internal field reduction in the nanorods sample plays a minimal role in the emission enhancement. As the temperature increased to 300 K, the carrier lifetimes were further shortened to 8.7 and 16.5 ns for the nanorod and as-grown samples due to the increase of the non-radiative recombination rate in the nanorod structures. The relatively larger non-radiative recombination rate at room temperature for the nanorod sample was probably due to the increasing surface recombination around the periphery of the nanorod. Generally, reduction of the internal PZ field facilitates a better wavefunction overlapping of electrons and holes in the green emission nanorod MQWs that could result in the increase of the emission efficiency and enhancement in the PL emission intensity of the nanorods. However, the PRTL measurement results reveal that the reduction of the internal PZ field could not be large enough to enhance the radiative recombination process in the green emission nanorods. As a result, the internal quantum efficiency of the nanorod sample at room temperature could not be improved, indicating that the PL intensity enhancement observed from the nanorod sample could result from the increased emission surface of the nanorod structure.

4. Fabrication and characteristics of AN-based nanorods LED

In this section, we based on the nanorod fabrication technique continuously and introduced a novel method combining ICP-RIE and the PEC wet oxidation process with self-assembled Ni metal islands to fabricate InGaN/GaN nanorod LEDs. Figure 11 shows the normalized PL spectrum of the as-grown LED sample, and nanorod

LED samples made with and without the PEC process measured at room temperature. A HeCd laser (325 nm) was used with an excitation power of 25 mW and the power density of 1.5 Wcm–2. The PL emission peaks of the InGaN/GaN active layer were bserved at 449.0, 445.2 and 440.4 nm for as-grown samples, and nanorods samples made without and with the PEC oxidation process, respectively. The PL peak intensities of InGaN/GaN MQW active layers in nanorods made with and without the PEC oxidation process were enhanced by factors of approximately six and five times compared with as-grown LED samples. The blue-shift phenomena were observed for both the nanorod LED samples made with and without the PEC oxidation process, and the blue-shift values were 3.8 nm (20 meV) and 8.6 nm (50 meV), respectively. The blue shift might be caused by the partial reduction of the piezoelectric field by the strain release in the nanorod structures Figure 12 shows the room-temperature EL spectrum of the as-grown LED and nanorod LED samples made with the PEC oxidation process at an injection current of 1 mA. The inset of figure 12 shows the emission image of the InGaN/GaN MQW nanorod LED. It shows that the PEC oxidation process can effectively form oxidation layers to isolate the nanorods and facilitate contact formation. The EL intensity of the nanorod LED made with the PEC process was about 1.76 times that of the as-grown LED

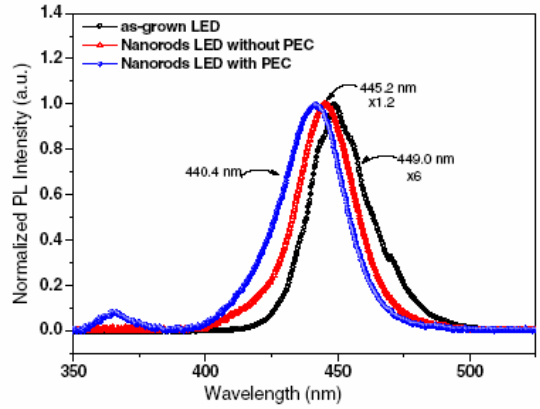


Figure 11. Normalized PL intensity spectra for as-grown LED and nanorod LEDs made with and without the PEC process at room temperature.

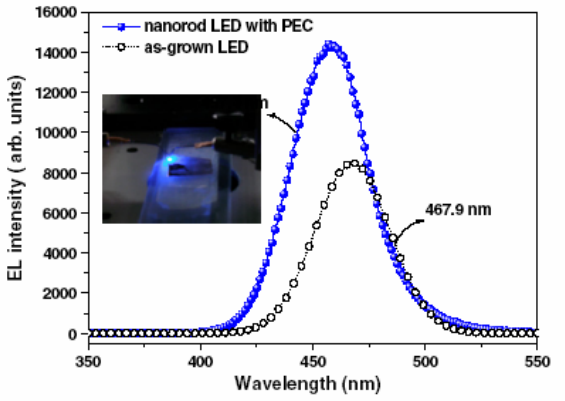


Figure 12. The EL intensity spectra for as-grown LED and nanorod LED made with the PEC process at room temperature. The inset shows a photographic image of the blue emission from an InGaN/GaN MQW nanorod LED at 1 mA dc current.

III. Fabrication and characteristics of the micro-cavity

1. **Successfully improved the reflectivity of GaN/AlN DBR reaches about 97% by the insertion of the nano-scaled super-lattice.**

The crack-free distributed Bragg reflectors (DBR) structure was successfully grown. Insertion of three sets of AlN/GaN superlattice is shown to significantly reduce the biaxial tensile strain, thereby resulting 20 pairs about 1.8 μm-thick, crack free high-reflectivity AlN/GaN distributed Bragg reflectors. The schematic structure of the grown DBR is shown in Fig.13. The surface also was measured by AFM shown in Fig. 14. The surface roughness R_a of this DBR sample is 2.5 nm and the grain size is 0.15 μm. The line profile shows the crack free. The cross-sectional TEM image of superlattice insertion was shown in Fig. 15. Reflectivity spectra of AlN/GaN DBR with three superlattice insertions were shown in Fig. 16. To study the distribution of reflectivity, we measured on three areas with 2mm diameter taken across the 2-inch wafer in the direction of a cross. Fig. 16 shows the reflectance spectra of three areas A, B and C, which are located in order from the center of a wafer to the radius direction. At area A, the peak reflectivity of 97% was obtained at wavelength of 399 nm and a stopband of 14 nm, and at area B, 97% at 405 nm. This peak wavelength was in good agreement with the required value. At area C, the

peak wavelength was 432 nm. This was caused by the difference of growth rate due to the temperature distribution of heater. Now the full vertical cavity surface emitting laser structure with crack-free DBR has been grown and fabrication of devices is in process.

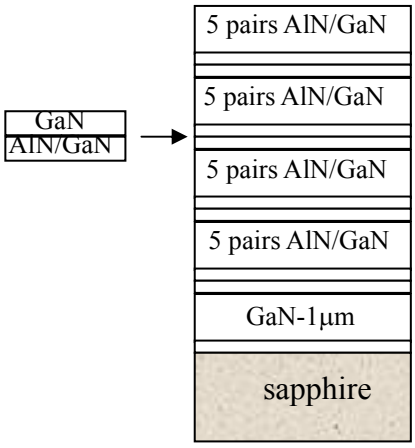


Fig. 13 Schematic structure of 20-pair Anlagen DBR with three super lattice insertions.

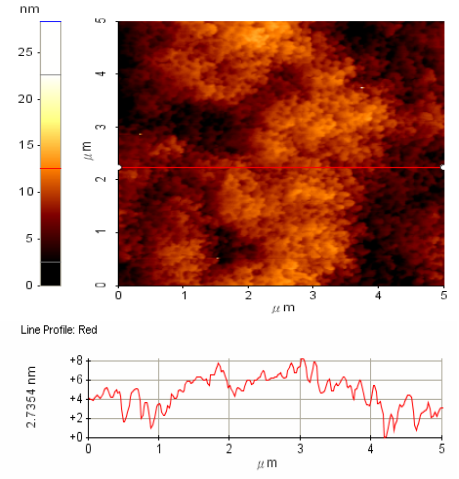


Fig. 14 The image of surface of DBR sample

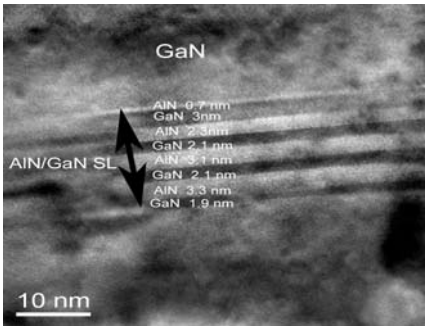


Fig. 15 Cross-sectional TEM image of DBR structure.

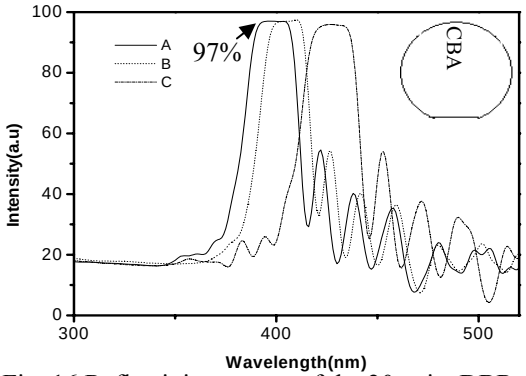


Fig. 16 Reflectivity spectra of the 20 pairs DBR with three AlN/GaN SLs measured at room temperature as a function of wavelength taken across the 2-inch wafer.

2. Successfully achieved laser operation by an optical excitation of the micro-cavity structure with hybrid mirrors.

The structure of the GaN-based VCSEL was grown in a vertical-type MOCVD system (EMCORE D-75). The polished optical-grade C-face (0001) 2-inch-diameter sapphire was used as substrate for the epitaxial growth of the VCSEL structure. The VCSEL structure composed of a 3λ cavity, a 20 pairs AlN/GaN DBR as bottom mirror and an eight pairs Ta_2O_5/SiO_2 dielectric mirror as the top DBR reflector. The schematic diagram of the full structure is shown in figure 17. During these processes, the peak reflectance of the AlN/GaN DBR structure and the Ta_2O_5/SiO_2 dielectric mirror were 97.5% and 94% at 450nm, respectively. Figure 18 shows the laser emission intensity as a function of pumping energy at room temperature condition. A distinct threshold characteristic was observed at the threshold pumping energy (E_{th}) of about 1.5μJ corresponding to an energy density of 53mJ/cm^2. The laser intensity increases linearly with the energy level beyond the threshold energy. Figure 19 shows the variation of emission spectrum with the increasing pumping energy. A dominant laser emission line at 448nm appears above the threshold pumping energy. The laser emission spectral linewidth reduces as the pumping energy above the

threshold energy and approaches 0.25nm at the pumping energy of 2.52E_{th}.

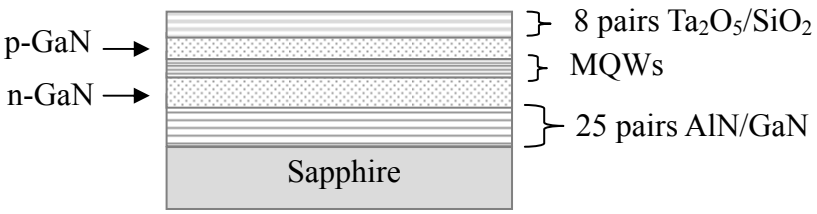


FIG.17. The schematic diagram of the overall structure.

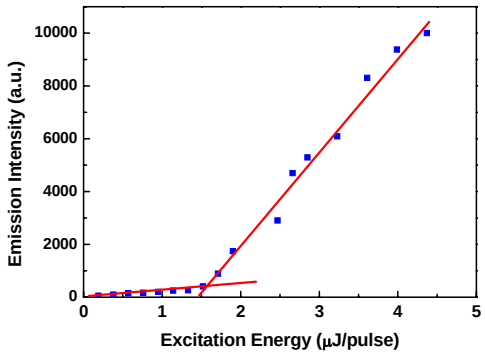


FIG.18. The light output intensity as a function of the pumping energy at room temperature.

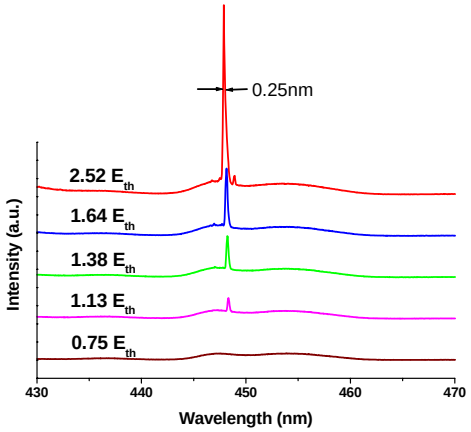
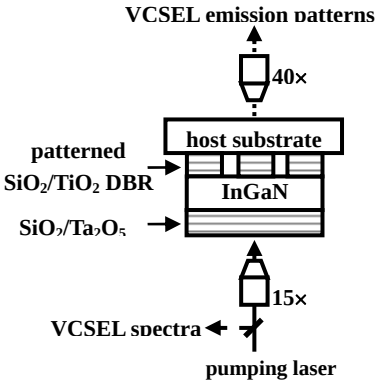


FIG.19. The variation of laser emission spectrum with the increasing pumping energy.

3. Successfully fabricated a micro-cavity with high reflectivity DBR using laser lift-off technique

The epitaxial structure of the GaN-based VCSEL was first grown on a (0001)-oriented sapphire substrate by metal organic chemical vapor deposition system. The structure consists of a 30-nm nucleation layer, 4-μm undoped GaN, a multiple quantum-well composed of 10 periods of 5-nm GaN barrier and 3-nm $In_{0.1}Ga_{0.9}N$ well, and 200 nm undoped GaN. Then a dielectric DBR consisting of 6 pairs of SiO_2 and TiO_2 was evaporated on the top of the grown structure to form a SiO_2/TiO_2 DBR/InGaN MQW/GaN/sapphire structure. The structure has a peak reflectivity of 99.5% at 414 nm. Then, an array of disk-like SiO_2/TiO_2 DBR mesas with 60 μm in diameter was formed. The patterned SiO_2/TiO_2 DBR/InGaN MQW/GaN/sapphire structure was then mounted onto a host fused silica substrate. The mounted sample was then subjected to a laser lift-off process. Finally, the second DBR consisting of 8 pairs of SiO_2 and Ta_2O_5 was deposited on the top of the polished GaN surface. The reflectivity of the SiO_2/Ta_2O_5 DBR at 414 nm is 97%. The complete structure of the GaN VCSEL with two dielectric DBRs is shown in Fig. 20(a).



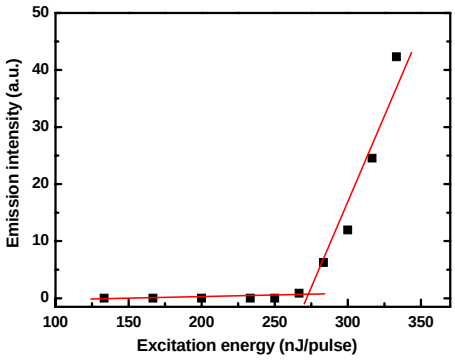


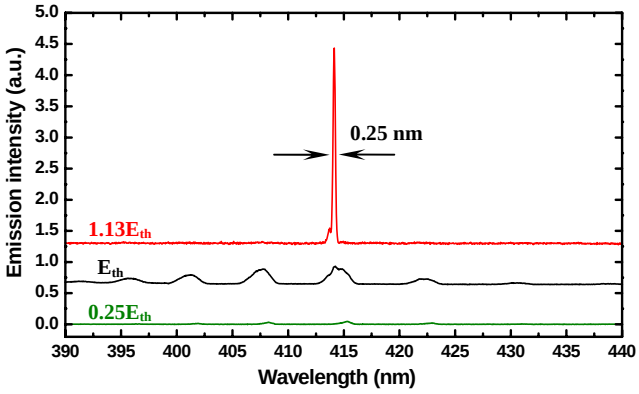
Fig. 20(a) **Fig. 20(b)**

Fig. 20(a) The setup for optical pumping of the GaN VCSEL with two dielectric DBRs. (b) Laser emission intensity as a function of the pumping energy operated at room temperature. The threshold pumping energy is about 270 nJ.

4. Successfully optically pumped InGaN-MQW VCSELs with two high –reflectivity dielectric DBRs

The structure above was successfully optically pumped and achieved lasing action at room temperature. The setup of optical pumping is shown in the figure 20(a). Figure 20(b) shows the laser emission intensity as a function of pumping energy at room temperature condition. A clear evidence of threshold condition occurs at pumping energy of 270 nJ corresponding to an energy density of 21.5 mJ/cm^2. The laser intensity increases linearly with the pumping energy level beyond the threshold energy.

Figure 21(a) shows the evolution of the VCSEL emission spectrum with the pumping energy at room temperature. At below threshold pumping energy, the spontaneous emission spectrum shows a multiple cavity modes with a mode spacing of about 7 nm and a linewidth of about 0.8 nm. This mode spacing corresponds to a cavity length of 4 μm which is nearly equal to the thickness of the GaN layer inside the cavity. The cavity quality factor (Q factor) estimated from the linewidth is about 518. As the pumping energy increases above the threshold, a dominant laser emission line appears at 414 nm with a narrow linewidth of about 0.25 nm. Figure 21(b) shows the 3-D isometric plot of the spatial intensity distribution of the laser beam.



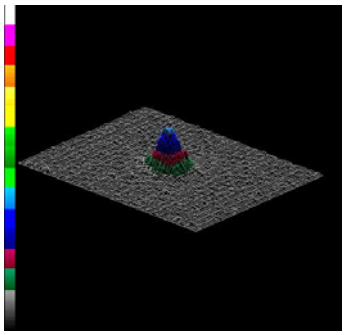


Fig. 21(a) **Fig. 21(b)**

Fig. 21(a). Emission spectra from the GaN-VCSEL at various pumping energy. (b) shows the 3-D isometric plot of the spatial intensity distribution of the laser beam.

III. Fabrication and characteristics of the micro-cavity

1. GaN quantum whispering gallery light emitting laser formed by photo-enhanced wet chemical oxidation and crystallographic etching

Combined with photo-enhanced wet chemical oxidation and crystallographic etching, we demonstrated GaN microcavities with various geometries, including Fabry-Perot cavity with vertical mirror facets of (10-10), faceted hexagon, and cylindrical cavities with smooth vertical sidewalls. Stimulated emission due to resonance with whispering gallery (WG) modes in the above cavities was observed under optical pumping with a 266nm Nd:YAG laser. Increase of the mode spacing and suppression of the side mode emission intensity were observed with device size as small as to 2μm.

As shown in Fig.22, the stimulated emission at ~ 372nm was observed at room temperature in the 5μm size hexagonal micro-facet cavity with a pumping threshold of~ 10MW/cm^2 and full width at half maximum (FWHM) ~0.9nm. Note the integrated peak intensity in the stimulated emission regime increases roughly with a relation $I_{stimu} \sim I_{pump}^2$, revealing a dominant mechanism by electron-hole plasma scattering, i.e., $|\langle \Phi_e \Phi_h | p | \Phi_e \Phi_h \rangle|^2$ Compared with a Fabry-Parot cavity made of the same (10-10) etched facets and optical length, the lasing threshold in the former is lower by 20%.

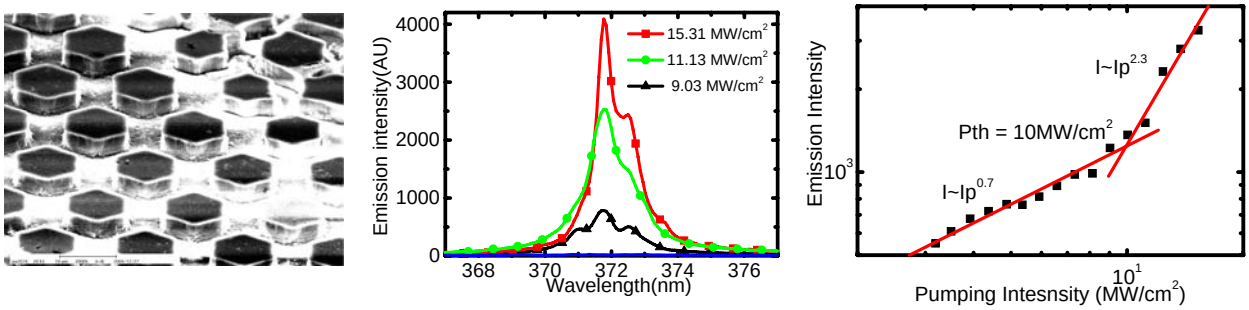


Fig. 22(a) SEM image of 5 μm hexagonal microcavity, (b) the PL spectrum exhibits mode spacing ~ 0.6 nm and (c) pumping threshold ~10MW/cm^2. The emission intensity increases with the relation $I \sim I_p^{2.3}$

2. Gallium nitride microcavities formed by photoenhanced wet oxidation

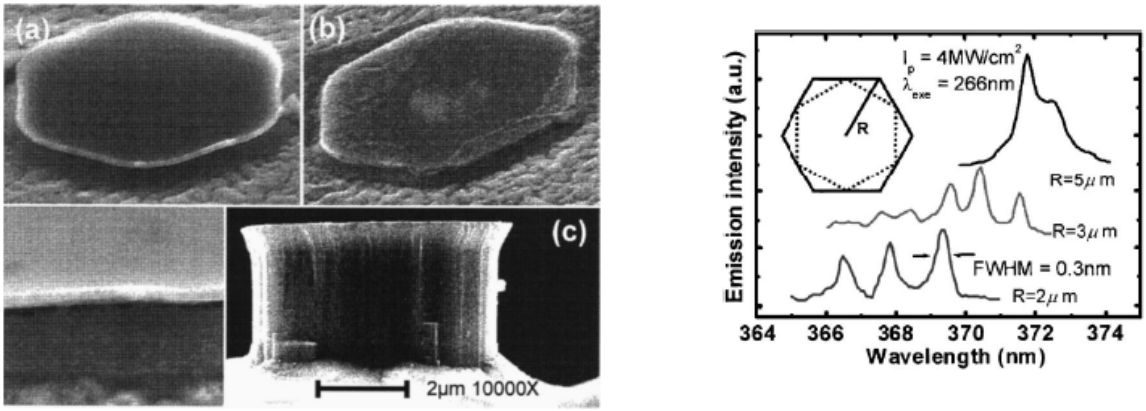


Fig. 22 Top view of SEM micrograph showing GaN hexagonal cavities after dissolving the PEC-grown oxide in (a) CH3COOH and (b) molten KOH. Inset: magnified cross-sectional SEM micrograph revealing an optically smooth sidewall in (a). (c) Cross-sectional SEM micrograph of a typical hexagonal GaN cavity to be used in the micro-photoluminescence study. The hexagon side length is 2 μm.

Fig. 23. Cavity size dependent emission spectra of GaN hexagons with radius *R*=5, 3, and 2μm measured at an intensity *I*~4 MW/cm2 of 266 nm YAG laser. The spectra have been vertically shifted for comparison.

Since the oxidized GaN layer can be dissolved in dilute acid or base solutions, a combination of the repeated photoenhanced wet oxidation and dissolution (etching) can thus be a promising route for the realization of GaN microcavities. Illustrated in Fig. 22 are the SEM micrographs showing the top view of GaN hexagonal microcavities formed by dissolving a 1-μm-thick oxidized GaN structure in (a) dilute CH_3COOH solution and (b) molten KOH at 180 °C for 1 min, respectively. The magnified cross-sectional SEM micrograph in the inset of Fig. 22(a) indicates a smooth sidewall can be retained by this proposed method. Except for a partial removal of the Ti mask by a short time immersion in molten KOH, no apparent difference can be found on the sidewall smoothness with respect to the choice of oxide dissolving solutions used in Figs. 22(a) and 22(b). These observations elucidate a principle to retain smooth GaN facets by slowly photo-oxidizing the nonpolar GaN planes at a rate much less than 1 nm/min. In comparison, for the polar $(0001)_{GaN}$ plane where the photoenhanced oxidation rate can proceed at a rate of 1 nm/min or higher, a wavy oxidized surface can be observed due to a localized, nonuniform distribution of the photoexcited carriers and reactants. Illustrated in Fig. 22(c) is one such hexagon of 2 μm radius, showing a smooth, vertical sidewall and inclined $(1\text{-}103)_{GaN}$ facets near the cavity pedestal.

Illustrated in Fig. 23 are the cavity size dependent luminescence spectra of GaN hexagons, revealing the characteristic peaks of WG modes in resonance with the GaN emission spectrum. Note a mode spacing of 0.74, 1.1, and 1.5 nm, respectively, are clearly discernible with a reduced hexagon radius of *R*=2, 3, and 5 μm at a constant pump intensity *Ip*~4 MW/cm2. These data agree well with a theoretical analysis by enforcing an optical path _shown in the inset of Fig. 23 to have a total phase shift equal to an integer multiple of 2π and thus to ensure total internal reflections inside the GaN microcavities.

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(六) 與國外學術合作

Prof. S. C. Wang, the leader of this three year project, already achieved an agreement with Prof. Yamamoto of Stanford University on cooperation of developing next generation GaN single photon emitter. One graduate student and Prof. Lu have been visited his lab for few months research to conduct preliminary and measurement experiment. The experience gained from Prof. Yamamoto on the GaAs-based QD microcavity device will be very useful for this effort and will ensure the successful outcome of this experiment. Besides, the research group had collaborated with Prof. K. Iga of Tokyo Institute of Technology, who is the first one to demonstrate the VCSEL structure, for GaN blue VCSEL. We had also collaborated with Prof. S.L. Chuang of UIUC, who got the excellent efforts of slow light in fiber communication, for the fabrication and performance measurement of VCSEL.

(七) 計畫成果自評

本計畫第一年預定目標如下：

1. 建立具備光學微共振腔之低維氮化鎵量子點、柱結構生長與製作，包括氮化鎵DBR反射膜與量子點之磊晶成長研究。
2. 氮化鎵面射型雷射結構之製程研究。
3. 以自組式光致氧化技術，生長二維奈米尺度之AlGaO、InGaO/GaN 量子柱結構。

本計畫第二年預定目標如下：

1. 光學微共振腔之低維氮化鎵量子點、柱結構生長與製作，包括氮化鎵 DBR 反射膜與量子點之磊晶成長及其發光元件製作之研究。
2. 建立光學微共振腔結構之物理性質量測與分析。
3. 氮化鎵面射型雷射結構之光學與電性特性研究。
4. 生長 AlGaO、InGaO 等光致自然氧化薄膜技術，研究其對於光學微型共振腔之表面保護、光學係數匹配，以及對於光學增益係數之提昇。

本計畫第三年預定目標如下：

1. 製作氮化鎵基量子點與面射型雷射元件
2. 分析研究量子侷限可控制光子輻射現象
3. 與史丹佛大學 Yamamoto 教授合作展示可控制光子輻射

在相關研究人員包括所有計畫共同主持人、博士後研究員、數十位博碩士生在這三年來的努力之下，所完成的成果相當豐碩，包括成功利用有機化學氣相沈積系統成長高密度氮化銦鎵量子點、利用乾式蝕刻方式以及自組成奈米遮罩蝕刻出直徑約 100 nm 的奈米柱並研究其物理性質（其中奈米柱裡包含多重量子井（發光層）），並對其發光機制與光學特性作完整的探討、利用奈米尺寸之超晶格插入成長出高反射率無裂縫之 AlN/GaN DBR 多層反射膜、氮化鎵微共振腔發光元件之製造與達到光激發面射型雷射、以及利用光致氧化與蝕刻製作出氮化鎵共振腔並達雷射輸出，此與原計畫所預定的目標已幾乎相符，其中面射型雷射的成功製作更可說明目前的研究成果與能力已能與世界許多一流之研究團體相提並論，本研究團隊再奈米尺寸下的元件製作包括兩種不同反射鏡之面射型雷射、奈米柱元件和利用光電化學氧化製作之微共振腔的研究成果以發表總計數十篇的國際期刊論文，應邀

出席數十場國際研討會並發表論文，在計畫期間所培養出來之碩博士生超過三十名，對於過內在學術上以及產業界均有相當大的助益。同時，本團隊和史丹佛大學 Yamamoto 教授的研究團隊在過去三年內進行相當密切的合作，除了有多位博士生到該實驗室進行實驗外，本團隊之盧廷昌亦到該實驗室進行數月的短期研究，對於本團隊在這方面的研究有很大的助益。對氮化鎵面射型雷射的微共振腔結構，以及利用本團隊之有機化學氣相沉積系統成長之量子點的量子侷限現象，和利用本研究團隊研發之奈米柱結構在特性上做相當深入的研究。

(八) 研究成果紀錄----附件一

附件一

「氮化鎵介觀尺度下量子局限結構之光子幅射可控性研究」研究成果紀錄

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共同主持人：孟心飛，彭隆瀚，林恭如，郭浩中

計畫執行期限：92/08/01~96/07/31

填表日期：

研究成果		92 年度	93 年度	94 年度	95 年度	總計
期刊論文	國內(篇數)	1	0	0	0	1
	國際(篇數)	10	17	10	27	64
會議論文	國內外(篇數)	0	5	16	23	44
智慧財產權	專利(案數)	0	2	1(申請中)	3(申請中)	6
	技術移轉(件數)	0	0	0	0	0
人才培育	博士生培育(人數)	4	4	3	3	14
	碩士生培育(人數)	7	6	5	5	23

註：人才培育人數請勿重複計算

發表之期刊論文列表

註：請按發表時間先後順序填寫，每篇請依作者姓名(主要作者請以粗體字標示)、期刊年份、題目、期刊名稱、起迄頁數、期刊資料庫類別(**SCI**、**SSCI**、**EI**…)之順序填寫。

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專利列表

類別	專利名稱	申請日期	專利申請國	申請案號/專利號碼	申請人	專利期間	備註
	形成奈米級粗化面的製程方法及其應用	2004/07/14	台灣	I278908	余長治 林仲相 黃泓文 郭浩中 王興宗		專利 公告
	Ⅲ族氮化物系反射鏡之製法	2005/12/05	台灣	200723624	黃根生 姚忻宏 郭浩中 王興宗		專利 公開
	製作包含透明導電玻璃及無裂縫氮化鋁/氮化鎵系列反射鏡之可電激發面射型雷射		台灣		鄭柏孝 盧廷昌 郭浩中 王興宗		申請中
	以啁啾式週期模態延展層實現 L 型近場光型之高功率高效率半導體雷射		台灣		盧廷昌 陳瓊華		申請中
	利用圖案化藍寶石基板提升量子井結構之光萃取效率		台灣		柯宗憲 盧廷昌 郭浩中 王興宗		申請中

	利用光電化學氧化技術製作可電激發之奈米柱發光二極體				黃泓文 盧廷昌 邱清華 郭浩中 王興宗		申請中

註：「類別」請填入代碼：(A)發明專利(B)新型專利(C)新式樣專利。

技術移轉列表

產出年度	技術名稱	移轉年度	授權單位	被授權單位	合約期間	繳庫金額			備註
						先期技術授權金	技術移轉授權金	合計	

促進民間投資

產出年度	技術移轉、關鍵技術、產品名稱	移轉年度	廠商名稱	促進投資金額（如有分年請述明）	廠商連絡窗口（姓名、電話、職稱）	投資內容概述

產學研合作列表

年度	推動計畫名稱	計畫投入經費（仟元）	執行單位名稱	計畫主持人	合作廠商/研究單位/學術單位名稱	廠商/研究單位/學術單位連絡窗口名稱(姓名、電話、職稱)	合作單位投入金額	備註
94	加速高效率光源應用之氮化鎵LED先進技術開發計畫	350,000/年共一年	交大光電	郭浩中	工研院/交大光電	光寶科技/交大/郭浩中、31986、副教授	350,000/年共一年	
95	應用奈米科技製作節能與新穎高效能發光二極體	7,200,180/年共2年	交大光電	王興宗	晶元光電/交大光電	晶元光電/交大/王興宗、56320、教授	2,458,400/年共2年	
95	利用雷射剝離和為結構粗化技術來發展高效能的發光二極體	1,320,000/年共一年	交大光電	郭浩中	光寶科技/交大光電	光寶科技/交大/郭浩中、31986、副教授	1,320,000/年共一年	
95	高效率低成本ⅢV族半導體太陽能電池關鍵技術開發計畫	909,000/年共一年	交大光電	郭浩中/盧廷昌	禧通科技/交大光電	禧通科技/交大/郭浩中、、31986、副教授，盧廷昌、31234、助理教授	447,000/年共一年	
95	高功率雷射二極體關鍵技術開發計畫	909,000/年共一年	交大光電	盧廷昌	友嘉科技/交大光電	友嘉科技/交大/盧廷昌、31234、助理教授	447,000/年共一年	

國際合作

計畫名稱	技術移轉、關鍵技術、產品項目	合作單位名稱	年度金額（仟元）	總金額（仟元）	現況說明	備註

出席國際學術會議心得報告

計畫編號	NSC94-2120-M009-007
計畫名稱	氮化鎵介觀尺度下量子侷限結構之光子輻射可控性研究(3/3)
出國人員姓名 服務機關及職稱	光電工程學系王興宗教授
會議時間地點	95 年 2 月 8 至 95 年 2 月 9 日 美國休士頓
會議名稱	U. S. Air force & Taiwan Nanoscience Workshop
發表論文題目	

一、參加經過與感想

由國科會國家型奈米科技計劃辦公室與美國空軍科學研究辦公室合辦之 U. S. Air force & Taiwan Nanoscience Workshop 研討會於 2 月 8 日至 9 日在休士頓(Houston,Texas)舉行。此次研討會之目的在於建立雙方相關科技研究者之互動關係與交換研究心得，進而促進雙方之學術研究交流，參加人員逾百位，發表數篇口頭報告論文，及壁報論文發表，筆者應邀發參加並擔任 Session 2:Gan and InN Nanostructures 主席，亦發表一篇論文。

此次會議筆者對美國軍方在奈米科技上之研究與需求瞭解甚多，獲益不少。對國內在奈米科技研究所投入之研究資源與研究成果能獲美國軍方之肯定，筆者認爲甚爲難得。筆者於會後 2 月 10 日上午飛返國內。

二、帶回研究資料

筆者帶回此次研討會論文摘要一冊，可供索閱，另外大會將製作論文摘要及投影片 CD 彙集, 應於近期內寄送至與會人員，將來亦可索閱。

出席國際學術會議心得報告

計畫編號	NSC94-2120-M009-007
計畫名稱	氮化鎵介觀尺度下量子侷限結構之光子輻射可控性研究(3/3)
出國人員姓名 服務機關及職稱	光電工程學系王興宗教授及盧廷昌助理教授
會議時間地點	95 年 2 月 21 至 95 年 2 月 23 日 香港
會議名稱	Nano Technology and Japan Nano 2006 會議
發表論文題目	

出國會議經過及心得:

Nano Technology and Japan Nano 2006 會議，於 95 年 2 月 21 至 95 年 2 月 23 日於日本東京舉行。主要爲日本所舉辦國際型的交流，內容含蓋廣泛，主要參加者仍以日本本國爲主，其餘來自美國、歐洲、韓國、台灣，值得一提的是台灣來參加的人還不少，但大都爲壁報展示。由於與會的人士中許多來自日本的電子業巨擘，例如 Fujitsu，Sony，Toshiba 等，因此有許多的人詢問關於 RCLED 的特性以及應用的相關問題，討論非常熱烈!

同時也參與了其他 session 的討論。但由於 SSDM 的主題包含太過廣泛，我僅排了和光電相關的會議 。其中另我印象較深的是 NTT 在 Photonic crystal defect laser 中所能達到的高 Q 值，以及東京大學可製作中溫室連續操作的 PBC laser。另外 NTT 可在奈米線中製作量子點，並量測其 Exciton 和 biexciton 的特性，東京大學荒川教授實驗室報告了改良型的單光子發射器，可用於量子通訊的應用，也令人敬佩! 此外，poster session 則有許多來自台灣的成果。

此行的所在地東京熱鬧非凡，只可惜我停留期間，陰雨綿綿，無法一覽城市美麗高樓的天際線。最後，感謝國科會的經費資助，得以展現我們的研究成果，並有機會和國際交流!

出席國際學術會議心得報告

計畫編號	NSC94-2120-M009-007
計畫名稱	氮化鎵介觀尺度下量子侷限結構之光子輻射可控性研究(3/3)
出國人員姓名 服務機關及職稱	光電工程學系王興宗教授
會議時間地點	95 年 3 月 25 至 95 年 3 月 29 日 美國洛杉磯
會議名稱	OFC/NFOEC2007 會議
發表論文題目	

一、 參加會議經過與心得

OFC/NFOEC2007 會議於 3 月 25 日至 3 月 29 日在美國洛杉磯舉行。此會議爲國際上所知名的學術研討會。參加學者來自世界各地包括美國、日本、韓國、加拿大、歐洲等地的知名學者。本次會議包含了數十個科技、科學領域，且有數十家廠商進駐會場發展新產品，故參與的人員非常地多，會場討論氣氛熱絡，且互動情型良好。

此次會議筆者對國內在奈米科技研究所投入之研究與需求瞭解甚多，獲益不少，筆者認爲甚爲難得。會議回程，筆者與博士研究生轉赴史丹福大學與合作研究之 Prof. Yoshi Yamamoto 商談研究合事宜，並提供本研究室之新氮化鎵奈米結構樣本於 Prof. Yamamoto 做實驗，筆者亦與 Prof. Yamamoto 討論今後研究合作之課題與細節。

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二、 帶回研究資料

筆者帶回此次研討會論文摘要一冊，可供索閱，另外大會將製作論文摘要及投影片 CD 彙集, 應於近期內寄送至與會人員，將來亦可索閱。

出席國際學術會議心得報告

計畫編號	NSC94-2120-M009-007
計畫名稱	氮化鎵介觀尺度下量子侷限結構之光子輻射可控性研究(3/3)
出國人員姓名 服務機關及職稱	光電工程學系盧廷昌助理教授
會議時間地點	95 年 9 月 13 至 95 年 9 月 15 日 日本橫濱
會議名稱	2006 International conference on Solid State Devices and Materials
發表論文題目	

一、 參加會議經過與心得

2006 International conference on Solid State Devices and Materials 於 9/13-9/15 在日本橫濱舉行。此會議主要爲日本所舉辦國際型的交流，內容含蓋廣泛，主要參加者仍以日本本國爲主，其餘來自美國、歐洲、韓國、台灣，值得一提的是台灣來參加的人還不少，但大都爲壁報展示。我主要是再 9/13 下午發表一篇”Strong Ultraviolet Emission from InGaN/AlGaN Multiple Quantum well Grown by Multi-step process”，15 分鐘長的報告。該場的主持人爲 Paul Drude Inst.的 Ploog 教授，他在 GaN 的領域相當有經驗，我們在該會議前也交換了一些關於 AlN/GaN DBR 的成長與特性的資訊。另外，我在 9/14 的早上又發表一篇” High Performances of 650 nm Resonant Cavity Light Emitting Diodes for Plastic Optical Fiber Application” 。由於與會的人士中許多來自日本的電子業巨擘，例如 Fujitsu，Sony，Toshiba 等，因此有許多的人詢問關於 RCLED 的特性以及應用的相關問題，討論非常熱烈!

除了準備論文發表之外，我也參與了其他 session 的討論。但由於 SSDM 的主題包含太過廣泛，我僅排了和光電相關的會議 。其中另我印象較深的是 NTT 在 Photonic crystal defect laser 中所能達到的高 Q 值，以及東京大學可製作中溫室連續操作的 PBC laser。另外 NTT 可在奈米線中製作量子點，並量測其 Exciton 和 biexciton 的特性，東京大學荒川教授實驗室報告了改良型的單光子發射器，可用於量子通訊的應用，也令人敬佩! 此外，poster session 則有許多來自台灣的成果，下圖即爲我和成大奈微所的薛道紅博士(也是從交大光電所王興宗老師實驗室畢業)的合影。

此行的所在地橫濱熱鬧非凡，只可惜我停留期間，陰雨綿綿，無法一覽城市美麗高樓的天際線。但未來港 21 仍然展現了日本第一大港的旺盛活力。最後，感謝國科會的經費資助，得以展現我們的研究成果，並有機會和國際交流!

出席國際學術會議心得報告

計畫編號	NSC94-2120-M009-007
計畫名稱	氮化鎵介觀尺度下量子侷限結構之光子輻射可控性研究(3/3)
出國人員姓名 服務機關及職稱	光電工程學系王興宗教授及博士後研究員黃根生博士
會議時間地點	95 年 10 月 22 至 95 年 10 月 27 日 日本京都
會議名稱	International Workshop on Nitride Semiconductors 2006
發表論文題目	

一、會議經過及感想

筆者受日本應用物理學會之邀請參加由其主辦之 2006 年度氮化物半導體國際會議（International Workshop on Nitride Semiconductors 2006），並在會期間與瑞士 Lausanne 大學研究室之研究人員討論相關之課題與細節。

日本應用物理學會在日本舉辦的二年一度氮化物半導體國際會議，此次國際會議於 2006 年 10 月 22 日至 10 月 27 日在京都的國立國際會議中心內舉行。共有來自 20 多個國家總計約有 700 位從事氮化物半導體研究的研究人員參加，主會場有兩天的特邀請演講，包括 M. George Craford and R. GaKsa 都分別做了本領域的精彩演講。第三天和第四天 4 個分會場，筆者主要參加 Optical Devices, 共有 105 場邀請演講和口頭報告購及 160 篇的壁報展覽。筆者穿插參加了 Optical Devices 的研究分會，和到與會人士互相交換了相關研究的心得，在之後的研究上助益良多。

筆者在會議的 10 月 25 號下午在 Optical Devices 的分會發表一場口頭報告，報告筆者對利用高反射率的氮化鋁/氮化鎵和氧化鉭/氧化矽布拉格反射鏡混合型共振腔，並回答他們提出的問題。

此行除了在會發表之論文受國際重視外，並認識到相關研究的現況及方向，收穫頗佳。對在執行中的奈米計畫將助益不淺。

二、攜回資料

筆者帶回本會之論文集，可供有興趣的研究專家索取。

出席國際學術會議心得報告

計畫編號	NSC94-2120-M009-007
計畫名稱	氮化鎵介觀尺度下量子侷限結構之光子輻射可控性研究(3/3)
出國人員姓名 服務機關及職稱	光電工程學系王興宗教授
會議時間地點	95 年 11 月 12 至 95 年 11 月 17 日 美國舊金山
會議名稱	2006 年第五十三屆美國真空協會(American Vacuum Society, AVS)
發表論文題目	

一、 參加會議經過與心得

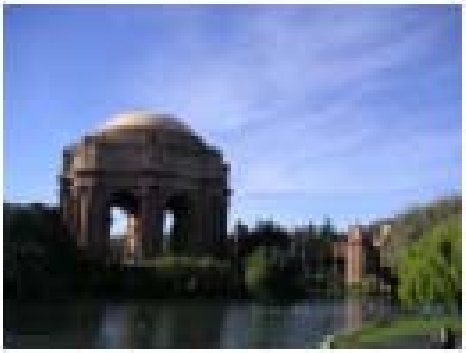
2006 年第五十三屆美國真空協會(American Vacuum Society, AVS)所舉辦的國際學術博覽會於十一月十二日至十一月十七日在美國舊金山舉行。此會議每年舉辦一次，爲國際上所知名的學術研討會。此次參加學者多達一千多位來自世界各地包括美國、日本、韓國、加拿大、歐洲等地的知名學者。筆者在會議的奈米科學範鑄中發表了一篇海報張貼論文，內容關於新化合物氧化銦的奈米鏈製作及其光學特性研究。本次會議包含了十四個科技、科學領域，且有多達四十家廠商進駐會場發展新產品，故參與的人員非常地多，會場討論氣氛熱絡，且互動情型良好。

會議的第一天爲註冊、報到及有少數演講廳舉辦學術研究發表，內容爲生物材料之領域。第二天、第三天則所有的演講廳均安排了講者演講，由於場次相當地多，且有些會在同一時間舉行，故筆者則根據自己實驗室所要發展的方面作考量，結合自己未來規劃的研究方面來選擇，其中對於美國聖地亞國家實驗室所發表的一篇關於利用 MOCVD 所成長三五族半導體奈米線材料有很深刻的印象，該主題利用金奈米粒子作爲觸媒的方式成功成長出 GaAs、GaN、AlGaN 等三五族半導體之奈米線陣列，並製作電極利用奈米線連通後將電性量測出來，光性上亦有相當不錯的表現，而 AlGaN 奈米線陣列在完成後發光波長可控制在 290 nm 至 300 nm 左右，由於筆者實驗室主要致力於三五族半導體元件之開發與研究，故該發表論文的重點及一些條件與方式是十分值得我們參考的。會議舉行的第三天下午爲筆者研究成果的展覽時間，由於近來奈米材料及氧化鋅應用於太陽能電池及透明導電膜之題目十分熱門，故在展覽

期間不時有對筆者研究深感興趣的相關研究人員詢問，彼此也交換了許多寶貴的意見。第四天筆者則在會場中參觀了許多廠商進駐的攤位，筆者向許多廠商的駐守人員詢問問題及意見交流，整趟行程下來，對筆者有莫大的幫助。

二、攜回資料

筆著帶回此次會議收錄的相關學術論文一本與一些廠商資料可供國內有興趣的研究學著觀閱。



出席國際學術會議心得報告

計畫編號	NSC94-2120-M009-007
計畫名稱	氮化鎵介觀尺度下量子侷限結構之光子輻射可控性研究(3/3)
出國人員姓名 服務機關及職稱	光電工程學系盧廷昌助理教授
會議時間地點	95 年 12 月 9 至 95 年 12 月 10 日 香港
會議名稱	2006 年第五屆海峽兩岸奈米科學與技術研討會
發表論文題目	

一、 參加會議經過

盧廷昌撰

一年一度的 2006 年第五屆海峽兩岸奈米科學與技術研討會於十二月九日至十二月十日在香港的科技大學舉行。此會議每一年在兩岸三地舉辦一次，為兩岸三地在奈米科技方面的研究學者提供了許多相互交流的機會。本次會議包含了奈米科技許多包涵物理、化學、生醫及材料等不同的面相，會場討論氣氛熱絡，且互動情形良好。筆者為其中一位邀請演講者，在會議中發表本實驗室最新的以奈米製程技術製作氮化鎵發光元件的技術與發展，與台下學者交換了許多寶貴的意見，獲益良多，發表的論文內容如下：

Light enhancement in GaN-based emitters by nano-fabrication technique

We have achieved the light enhancement in two kinds of GaN-based emitters, including GaN laser diode (LD) and light emitting diode (LED), by nano-fabrication technique. Up to now, the nitride based light emitting devices, such as LDs and LEDs, still have different difficulties in the improvement of light output power and optical properties. On one hand, the major problem for the nitride based light emitting diodes is its low refractive index caused small critical angle (~23^{o}). In order to enlarge the escaping cone formed by the critical angle, we introduce the nano-process to roughen the P-GaN surface of our LED structure. This nano-roughening process is mainly performed by using Ni clusters as the etching mask and the excimer laser as the etching tool. We have demonstrated the light output power of the nano-roughened LED is 55% higher than conventional LED. On the other hand, GaN edge emitting laser shows only 10^{-5} of coupling efficiency of spontaneous emission. Recently, we have developed an optical pumped GaN vertical cavity surface emitting laser (VCSEL) and found the enhancement on optical properties compared to current edge emitting lasers. The GaN VCSEL is formed by growing a micro-scaled cavity with an AlN/GaN DBR by MOCVD and coating a Ta_2O_5/SiO_2 DBR using an e-gun. The GaN VCSEL shows a high quality factor of 760 and a strong coupling efficiency of spontaneous emission of about 10^{-2}. These results suggest our structure and processes are potential in the application of high efficiency light emitting devices.

此外，我也和兩岸三地的學者討論未來合作的機會，其中台大的孫啟光老師對我們製作的氮化鎵奈米柱很有興趣，可應用於奈米超音波的研究上；另外，也有許多學者和我討論在製程上共同合作開發的可能性。

會議的時間很短，且這是筆者第一次前往香港，深深被香港地狹人稠與高樓林立的景象所震攝，香港天氣與台灣差不多，而在地鐵上其實也與台北捷運相似，標示也十分清楚，非常方便，最令我印象深刻的是晚間在維多利亞港畔的幻彩詠香江的雷射燈光秀，每一棟高樓搖身一變成為五彩絢爛的主角，表演可說是精彩萬分。此外，我也到香港科技大學的無塵室參觀，這個無塵室是香港科技大學的設備中心，和交通大學的奈米設施中心的功能類似，只是科大的實驗室中的設備較為集中且完整！

二、攜回資料

筆著帶回此次會議收錄的相關學術論文一本可供國內有興趣的研究學著觀閱。

筆者發表論文之照片